A Cluster of 1.3 cm Continuum Sources in OMC1 South

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ABSTRACT

We present sensitive 1.3 cm radio continuum observations of the region OMC1 South (OMC-1S) in Orion using the Very Large Array in its B configuration. We detect eleven radio sources clustered in a $30'' \times 30''$ region, of which only three had been detected previously at radio wavelengths in deep 3.6 cm observations. The eight new radio sources are compact ($\theta_s \leq 0\rlap{.}''1$) and we set lower limits to their spectral indices, $\alpha > 0.8 \pm 0.3$ (with $S_\nu \propto \nu^\alpha$), that suggest that they may be optically-thick H II regions. However, one of the new sources exhibits significant circular polarization, indicating that gyrosynchrotron emission with large positive spectral indices may be an alternative explanation. Furthermore, we find that four other sources are associated with infrared sources of low bolometric luminosity that cannot drive an H II region. Finally, two of the sources previously detected at 3.6-cm are angularly resolved in the 1.3 cm image and their major axes have position angles that align well with large scale outflows emanating from OMC-1S. The radio source 143-353 has a major axis with a position angle consistent with those of the HH 202 and HH 528 flows, while the radio source 134-411 has a major axis with a position angle consistent with that of the low-velocity molecular outflow associated with the far-infrared source FIR 4.

Subject headings: stars: pre-main sequence – ISM: jets and outflows – ISM: individual: (OMC-1S) – ISM: HII regions – stars: radio continuum

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1. Introduction

The OMC-1S region is a high-luminosity ($\sim 10^4\ L_\odot$) source at infrared and submillimeter wavelengths in the Orion Nebula that is still actively forming high-mass stars (Bally, O'Dell, & McCaughrean 2000). It is located about 1' to the SW of the Trapezium and several powerful molecular outflows (Ziurys, Wilson & Mauersberger 1990; Schmid-Burgk et al. 1990; Rodríguez-Franco, Martín- Pintado & Wilson 1999) appear to emanate from this region, probably driven by highly embedded young stars (Bachiller et al. 1996). Numerous H_2O masers (Gaume et al. 1998) are also known to be present in OMC-1S.

The survey of proper-motions in the Orion Nebula (Bally et al. 2000; O'Dell & Doi 2003) revealed that at least six relatively large Herbig-Haro outflows (HH 202, HH 269, HH 529, HH 203/204, HH 530, and possibly HH 528) are originating from a region only a few arcseconds across in OMC-1S that O'Dell & Doi (2003) locate at $\alpha_{2000} = 5^h 35^m 14^s.56$, $\delta_{2000} = -5^\circ$ 23'54" with a positional error of $\pm 1\rlap{.}''5$. O'Dell & Doi (2003) refer to this region as the Optical Outflow Source (OOS). Although embedded objects (i. e., TPSC-1, Lada et al. 2000) have been detected in this region, the actual identification of the powering sources of the outflows remains uncertain.

From their analysis of 3.6 cm radio continuum VLA archival observations of Orion, Zapata et al. (2004) found three faint sources in the OMC-1S region. Two of them (VLA 13 and VLA 15) are located near the position for the OOS (and thus may be related to the sources that power the multiple outflows that emanate from this region). The other source (VLA 10) is coincident, within the millimeter wavelength positional error, with the source FIR 4 (Mezger et al. 1990), the presumed exciting source of the low-velocity CO outflow detected by Schmid-Burgk et al. (1990).

In this paper we present new observations of the OMC-1S region at 1.3 cm that reveal a cluster of eleven sources, of which eight are new detections in the radio. This result supports the expectation that a cluster of young, possibly massive stars should be embedded here. Our results also allow us to improve our understanding of the nature of the three sources previously found at 3.6 cm by Zapata et al. (2004).

2. Observations

The observations were made with the Very Large Array of NRAO[1] in the continuum mode at 1.3-cm during 2003 December 23 and 27. At these epochs, the VLA was in the B configuration. The phase center of the observations was $\alpha(2000) = 05^h\ 35^m\ 14\overset{s}{.}0$; $\delta(2000) = -05^\circ\ 24'\ 03''$, very close to the center of the new radio cluster. The absolute amplitude calibrator was 1331+305 and the phase calibrator was 0541-056, with a bootstrapped flux density of 0.75 ± 0.01 Jy.

The data were analyzed in the standard manner using the AIPS package of NRAO and self-calibrated in phase and amplitude. The images were made using only visibilities with baselines larger than 90 kλ, thus suppressing the emission of structures larger than $\sim 2''$. This procedure is necessary given the presence of complex, extended emission in the region. Furthermore, we used the ROBUST parameter of IMAGR set to 0, in an optimal compromise between sensitivity and angular resolution. The resulting image rms was 70 μJy beam^{-1} at an angular resolution of $0\overset{''}{.}30 \times 0\overset{''}{.}25$ with PA $= -5^\circ$. In the OMC-1S region we detected a total of 11 sources (see Figure 1). The positions, flux densities (at 1.3 cm and 3.6 cm), and spectral indices of these radio sources are given in Table 1. The 3.6 cm flux densities are from Zapata et al. (2004). To refer to these sources we have adopted a position-based nomenclature after the convention of O'Dell & Wen (1994). In Table 2 we list counterparts (objects within $0\overset{''}{.}5$ of the radio source) for the 1.3 cm sources. Only the radio source 143-353 has an optical counterpart in the HST optical images of O'Dell & Doi (2003).

3. On the Nature of the 1.3 cm Sources

Following Windhorst et al. (1993), we roughly estimate that the expected number of 1.3 cm background sources above a flux density of S is given by $\langle N \rangle \simeq 1.0 \times 10^{-3}\ (S/mJy)^{-1.2}$ $arcmin^{-2}$. Then, the probability of finding a source with flux density equal or larger than 0.36 mJy (the weakest source reported) in a $30'' \times 30''$ region is only $\sim$0.001, so we conclude that most probably all sources are associated with Orion. Of the eleven sources detected at 1.3 cm in the field, only three have been previously detected in the radio at 3.6 cm. The sources 131-411 (= VLA 10), 141-357 (= VLA 13) and 143-353 (= VLA 15) were detected in the sensitive 3.6 cm image of Zapata et al. (2004). All the new eight sources have steep positive spectral indices, which explains why they are detected at 1.3 cm but not at 3.6

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cm. From comparison with the 3.6 cm upper limits we set lower limits to their spectral indices, $\alpha > 0.8 \pm 0.3$ (with $S_\nu \propto \nu^\alpha$). This suggests that they may be optically-thick H II regions powered by embedded B-type stars. This proposition is consistent with the fact that three (136-359, 139-357, and 141-357) of the eight newly found sources are closely associated with the water vapor masers reported by Gaume et al. (1998). However, one of the sources (140-410) was found to show large ($\sim$20%) right circular polarization. This emission is believed to trace gyrosynchrotron emission from active magnetospheres of young, low mass stars. Furthermore, from the results of Smith et al. (2004) and Robberto et al. (2004) we find that four other sources (136-356, 136-359, 139-357, and 144-351) are associated with infrared sources of low bolometric luminosity that cannot drive an H II region. We are thus left with the possibility that some of these new sources are not optically-thick H II regions, but may be sources of gyrosynchrotron emission or ionized outflows from low-mass stars. We tried unsuccessfully to look for large temporal variations by comparing the December 23 and December 27 data. Observations at several wavelengths and time monitoring are required to firmly establish the nature of these sources with steep, positive spectral indices.

4. Thermal jets

Only two sources are clearly resolved in the 1.3 cm data: 143-353 (= VLA 15), with deconvolved dimensions of $0\rlap{.}''75 \pm 0\rlap{.}''05 \times 0\rlap{.}''30 \pm 0\rlap{.}''03; PA = 144^\circ \pm 4^\circ$, and 134-411 (= VLA 10), with deconvolved dimensions of $0\rlap{.}''28 \pm 0\rlap{.}''02 \times 0\rlap{.}''09 \pm 0\rlap{.}''03; PA = 25^\circ \pm 5^\circ$. For the other radio sources we derive a typical upper limit of $0\rlap{.}''1$ for their angular size. As we will show, the orientation of these two sources suggests they are thermal jets that are powering important outflows in the region.

4.1. 143-353

Within the complex of six major outflows that originate from the OOS region (O'Dell & Doi 2003), this feature aligns with both HH 202 and HH 528. HH 202 is the prominent HH object in the central region of the Orion Nebula and it was one of the first in Orion to be identified as such (Cantó et al. 1980; Meaburn 1986). Rosado et al. (2001) have proposed that HH 202 forms a bipolar outflow with HH 203/204, but the fact that both HH 202 and HH 203/204 are blueshifted and the excellent alignment of the 1.3 cm source 143-353, with HH 202 on one side of the radio jet and HH 528 on the other side makes this suggestion less likely.

Examination of Figure 1 of O'Dell & Doi (2003) shows that the PA for HH 202 is $326° \pm 4°$ and that of HH 528 is $144° \pm 4°$, i.e. that they are almost exactly opposite in direction along a common axis and very well aligned with the major axis of the radio source 143-353 ($144° \pm 4°$, see Figure 2). The proper motion data of O'Dell & Doi (2003) show that the tip of HH 202 is moving at 51$\pm$13 km s^{-1} towards $322° \pm 25°$ and the entire HH 528 object is moving at 25$\pm$14 km s^{-1} towards $159° \pm 35°$, which means that the two objects are moving away from one another and along their axis of orientation.

The radio source 143-353 has a nearly coincident optical counterpart, best seen in Figure 20 of Bally et al. (2000) as a bright emission line filament to the northwest from the source marked 9 in that figure. Our source 143-353 is the northwest portion of an irregular filament $3\rlap{.}''2$ long, oriented towards $PA = 323° \pm 10°$. The optical source is $0\rlap{.}''8 \times 0\rlap{.}''2$ in angular size, and is visible on HST images in Hα, [OIII], [NII], [OI], and [SII]. Its orientation is $PA = 310° \pm 10°$. The tangential motion of the entire filament is 16$\pm$4 km s^{-1} towards $323° \pm 17°$ (O'Dell & Doi 2003)

It is difficult to assign a source for any of the outflows from the OOS region on the basis of the extrapolation of orientation vectors as there are multiple objects within the error ellipse for the region. However, the additional information of the optical and radio alignment of 143-353 with both HH 202 and HH 528 suggests a relationship. In terms of the direction of motion of the optical counterparts of 143-353, it is plausible that HH 202 is being driven by the source that produces 143-353. The much lower tangential velocity of 143-353 would require that we are actually seeing the material entrained on the outside of a smaller, higher velocity jet, a condition that would apply if this jet were passing through the dense layer near the main ionization front of the nebula.

A connection with HH 528 is suggested by the orientations, but 143-353 is moving in the opposite direction. However, there may be a common source for both HH 202 and HH 528 which also produces 143-353. HH 202 is known to have a high blueshift (the most accurate and recent determination is by Doi, O'Dell & Hartigan 2004). A truly bipolar source would mean that HH 528 would have a similar high redshifted velocity, for which there is no evidence. However, we do see blueshifted components from two other (HH 269 and HH 529) opposite moving features coming out of the OOS region (Doi, O'Dell & Hartigan 2004). The east-west orientation of those flows indicates a different source within the OOS, but the velocities indicate that some mechanism is operating that allows opposite flow with common blueshifted components. If this same mechanism applies to HH 202–143-353–HH528, then they too could be sharing a common source.

In general, thermal radio jets such as 143-353 are interpreted to mark the position of the exciting source. Indeed, the fact that the source is not optically-thin suggests it is fairly

dense and most probably directly associated with the exciting star. However, it is also possible that 143-353 is just part of a long jet, displaced from the exciting star. If this is the case, there is a good candidate star for producing the 143-353 jet. This is the object 145-356, which has been detected at K' (Source 9; McCaughrean & Stauffer 1994), L (Source 2; Lada et al. 2000) N (Source 60; Robberto et al. 2004), and three IR bands (Source 3; Smith et al. 2004). There is no radio counterpart to this source. This apparently stellar source is positioned so that 143-353 lies $5\rlap{.}''1$ at PA=307°. If one accepts the orientation of the extended jet and 143-353 as definitive, then this star is an excellent candidate for the source. If the optical proper motions indicate true tangential velocities, then the jet originated 700 years ago. If the proper motion of HH 202 is adopted (which is the better assumption if the optical material is entrained gas on the edge of the jet), then the age of the jet is 220 years.

4.2. 134-411

As mentioned before, three of the eleven 1.3 cm sources had been detected previously at 3.6 cm (Zapata et al. 2004). One of them, 134-411 (= VLA 10) has a spectral index of 1.9±0.1, consistent with an optically-thick H II region. However, its position and orientation suggest that this source is driving the low-velocity monopolar molecular outflow (Schmid-Burgk et al. 1990) that is centered in the 1.3 mm continuum source FIR4 (Mezger et al. 1990), located at $\alpha(2000) = 05^h\ 35^m\ 13\rlap{.}^s4; \delta(2000) = -05^\circ\ 24'\ 13''$. The PA of the major axis of 134-411 (see Figure 3) is $25^\circ \pm 5^\circ$, while that of the molecular outflow is 31° (Schmid-Burgk et al. 1990). The association of 134-411 with the outflow is also supported by its spatial coincidence with the cluster of high-velocity H_2O masers detected and discussed by Gaume et al. (1998).

5. Conclusions

Our results significantly alleviate the apparent lack of exciting sources of the multiple outflows that originate from OMC-1S. In particular, the source 143-353 could be driving the HH 202 and possibly the HH 528 flows, while the source 134-411 could be driving the low-velocity molecular outflow in the region. However, additional studies are required to identify the exciting sources of the multiple outflows and to firmly establish the nature of the objects in this new cluster of compact, steep positive spectrum radio sources in Orion.

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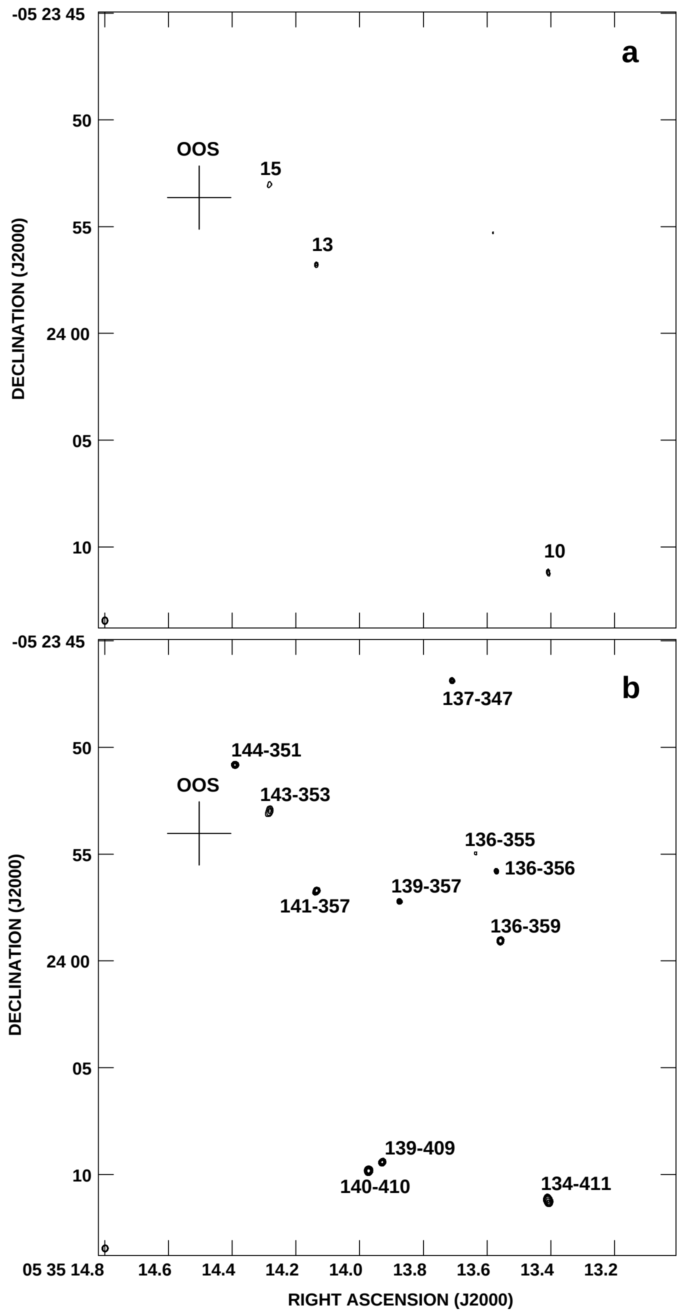

Fig. 1.— VLA continuum images at 3.6 cm and 1.3 cm of the OMC1-S region. The position for the OOS (O'Dell and Doi 2003) is indicated with a cross. The half power contour of the synthesized beams are shown in the bottom left corner of the images. **a.** The faint sources 10, 13 and 15 were reported at 3.6 cm by Zapata et al. 2004. The contours are -5, 5 and 6 times 50 μJy beam^{-1}, the rms noise of the image. **b.** The objects 136-359, 136-356, 136-355, 137-347, 139-357, 139-409, 140-410 and 144-351, are first reported as radio sources here. The contours are -5, 5, 6, 7, 8, 9, 10, 15, 20, 30 times 70 μJy beam^{-1}, the rms noise of the image.

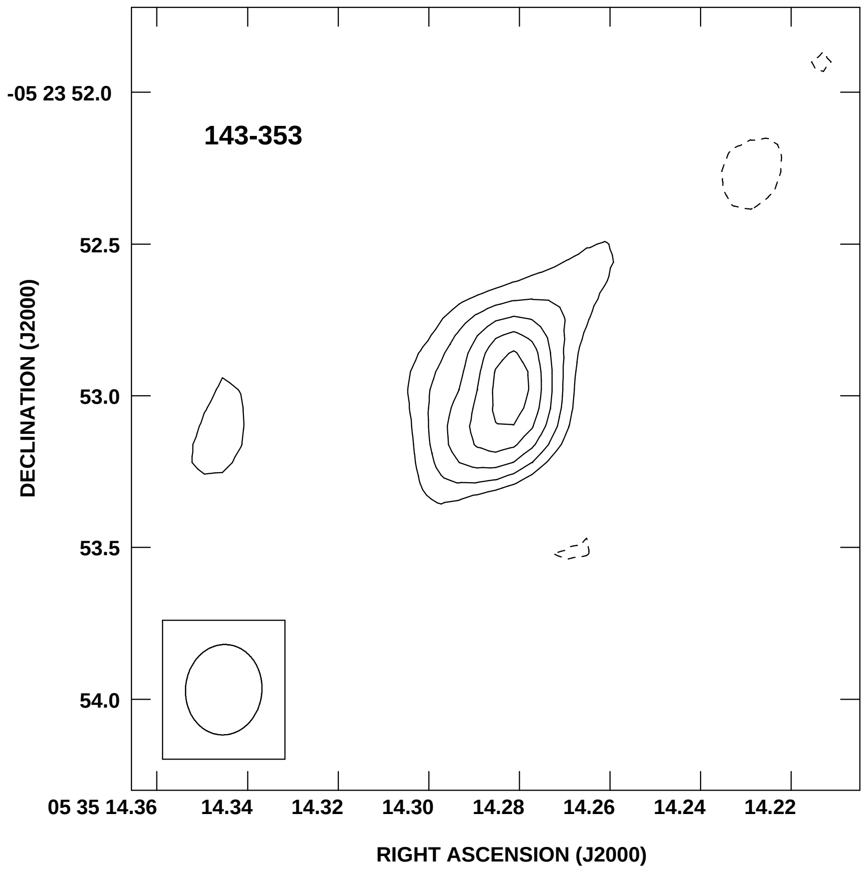

Fig. 2.— VLA continuum image at 1.3 cm of the source 143-353. The half power contour of the synthesized beam is shown in the bottom left contour. The contours are -4, -3, 3, 4, 5, 6, and 7 times 70 μJy beam^{-1}, the rms noise of the image. This source is proposed to be driving the HH 202 and possibly the HH 528 outflows. The position angle of HH 202 is $326^\circ \pm 4^\circ$ and that of HH 528 is $144^\circ \pm 4^\circ$, aligning well with the position angle of the major axis of the radio source, which is $144^\circ \pm 4^\circ$.

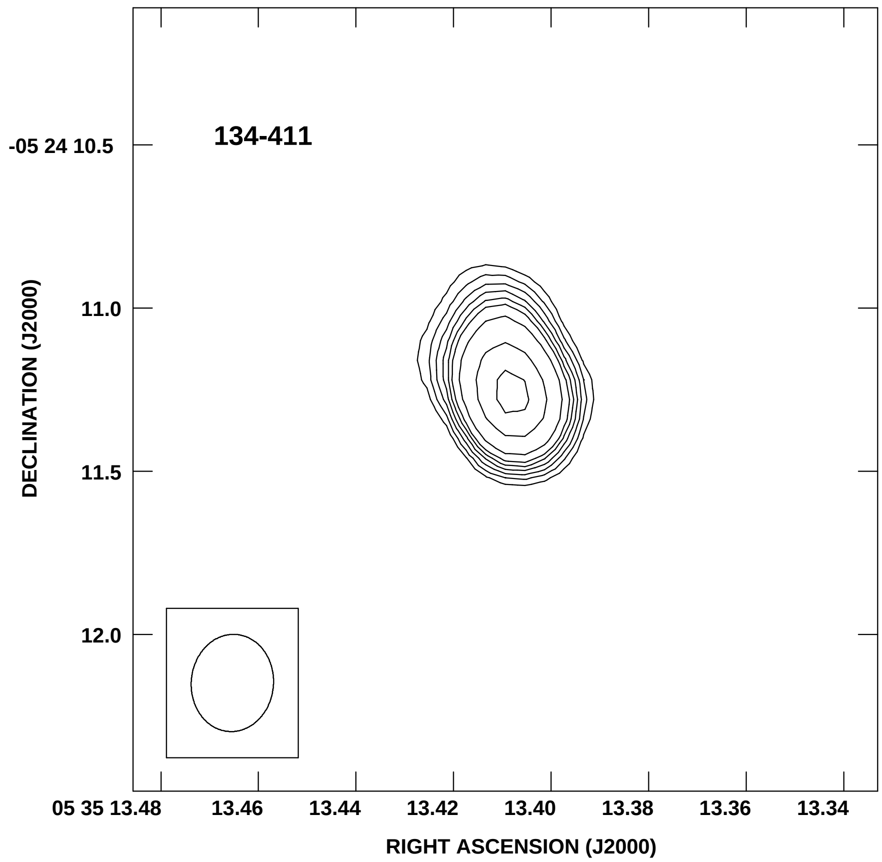

Fig. 3.— VLA continuum image at 1.3 cm of the source 134-411. The half power contour of the synthesized beam is shown in the bottom left corner. The contours are -4, -3, 3, 4, 5, 6, 7, 8, 10, 15, and 20 times 70 μJy beam^{-1}, the rms noise of the image. This source is proposed to be driving the low-velocity monopolar molecular outflow associated with the far-infrared source FIR 4. The position angle of the molecular outflow is 31°, in good agreement with the position angle of the major axis of this source, which is $25^\circ \pm 5^\circ$.

Table 1. Parameters of the VLA Sources Detected Detected at 1.3 cm

Radio Source	α_{2000} (h m s)	δ_{2000} ($^\circ$ $'$ $''$)	Flux Density[a] 1.3 cm (mJy)	3.6 cm (mJy)	Spectral Index 1.3 cm/3.6 cm
134-411	05 35 13.408	-05 24 11.27	2.07$\pm$ 0.06	0.33	1.9 $\pm$0.1
136-359	05 35 13.558	-05 23 59.06	0.93$\pm$ 0.04	$\leq$ 0.16	$\geq$ 1.8$\pm$0.3
136-356	05 35 13.571	-05 23 55.80	0.48$\pm$ 0.04	$\leq$ 0.16	$\geq$ 1.1$\pm$0.3
136-355	05 35 13.636	-05 23 54.94	0.36$\pm$ 0.04	$\leq$ 0.16	$\geq$ 0.8$\pm$0.3
137-347	05 35 13.709	-05 23 46.89	0.76$\pm$ 0.05	$\leq$ 0.16	$\geq$ 1.6$\pm$0.3
139-357	05 35 13.875	-05 23 57.21	0.67$\pm$ 0.04	$\leq$ 0.16	$\geq$ 1.4$\pm$0.3
139-409	05 35 13.930	-05 24 09.43	1.03$\pm$ 0.06	$\leq$ 0.16	$\geq$ 1.9$\pm$0.2
140-410	05 35 13.972	-05 24 09.84	1.63$\pm$ 0.06	$\leq$ 0.16	$\geq$ 2.4$\pm$0.3
141-357	05 35 14.135	-05 23 56.69	0.90$\pm$ 0.04	0.32	1.1$\pm$0.1
143-353	05 35 14.281	-05 23 52.93	1.60$\pm$ 0.06	0.30	1.7$\pm$0.1
144-351	05 35 14.391	-05 23 50.81	1.01$\pm$ 0.05	$\leq$ 0.16	$\geq$ 1.9$\pm$0.3

Note. — (a): Total flux density corrected for primary beam response.

Table 2. Counterparts of the 1.3 cm VLA Sources

Source	Counterpart[a]
134-411	VLA 10, GWV, FIR 4
136-359	F 370, GWV, SBSMH 4, MAX 42
136-356	SCH 18, TPSC 46, SBSMH 5, MAX 43
136-355	-
137-347	AD 2650
139-357	GWV, SBSMH 6
139-409	GWV
140-410	-
141-357	GWV, VLA 13
143-353	VLA 15, HST 143-353
144-351	SBSMH 2, MAX 58

Note. — (a): Sources at other wavelengths within $0.''5$ of the 1.3 cm sources. AD = Ali & Depoy 1995 (K-band); F = Feigelson et al. 2002 (X-rays); FIR = Mezger et al. 1990; GWV = Gaume et al. 1998 (water masers); HST = O'Dell & Doi 2003 (visible) MAX = Robberto et al. 2004 (10 and 20 μm) SBSMH = Smith et al. 2004 (8.8 and 11.7 μm) SCH = Schulz et al. 2001 (X-rays); VLA = Zapata et al. 2004 (radio 3.6 cm)